THE HYDROLOGICAL CONSEQUENCES OF URBANISATION: LUBLIN CASE STUDY (POLAND)

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Abstract

The paper presents the consequences of changes in water management in Lublin (Poland). The area's urban development and specific water management conditions (the concentration of large groundwater intakes in a relatively small area) have caused changes in the volume of groundwater resources, and a transformation of the hydraulic connection of groundwater with surface water. Anthropogenic changes in the discharge of rivers can also be observed. This concerns the Bystrzyca River and its tributaries: the Czechówka and Czerniejówka Rivers. The changes are particularly evident in the lower section of the catchment, within the depression cone. The natural regime of the Bystrzyca River is affected by the discharge of sewage water from the sewage treatment plant in Hajdów, and by surface runoff from the urban area. In periods without surface runoff, daily changes in the discharge from the Bystrzyca River are predominantly due to the disposal of post-sewage waters from the sewage treatment plant. The supply is determined by the daily rhythm of the functions of Lublin's inhabitants. Successive growth of weakly permeable surfaces in the city causes fast and increasing precipitation water runoff, particularly following intensive precipitation events and snowmelt. This results in a rapid increase in water stages in the Bystrzyca River below Lublin.

Key words: Lublin, urban hydrology, surface runoff, urban floods.

INTRODUCTION

The issue concerning the effect of cities on the environment, including water management, is extremely relevant (Cheng and Wang 2002; Akan and Houghtalen 2003; Russo et al. 2005; Cuo et al. 2008; Hollis 2010; Huong and Pathirana 2013). The general consequences of strong anthropopressure and the effects of urban development on the environment are commonly known. In extreme cases, they lead to the necessity of sourcing water from the outside catchment and to periodical water excess (Dobija 1975). The issue of water in cities, investigated by various fields of science, is most frequently defined as "urban hydrology". Urbanisation as a social and cultural process is manifest in the development of cities, the increase in their numbers, the growth of urban areas, and the increasing contribution of urban populations to the population as a whole. The urbanisation process directly or indirectly causes changes in water management not only in urban areas, but also in the surrounding ones. A consequence of dense development and the construction of roads and parking lots is an increase in non-permeable surfaces. It leads to the intensification of surface runoff and a considerable decrease in water infiltration into groundwater resources (McPherson ed. 1977; Deletic 1998).

A transformation of only 20% of the natural surfaces of the catchment may double the rate of outflow from the area (McPherson ed. 1974). Due to the systematically increasing contribution of cities' urban areas, the determination of the runoff dynamics, as well as the composition and concentration of substances contained in the water, is of considerable scientific and practical importance. Faster runoff from urban areas causes water accumulation. In certain conditions, it may cause inundations, high water levels, or even floods.

OBJECTIVE OF THE PAPER, STUDY MATERIALS AND METHODS

The objective of the paper is to determine the hydrological effects of urban development and infrastructure in Lublin. This particularly concerns groundwater and alimentation of rivers, runoff dynamics, and their effect on the rivers' discharge, as well as the effect of water management on the discharge regime of the Bystrzyca River below Lublin. The implementation of the task was based on measurements and hydrological, hydrochemical, and hydrogeological observations by the Department of Hydrology of the Maria Curie-Skłodowska University (MCSU), and on data from the Municipal Water and Sewerage Company in Lublin (MWSC) and the Institute of Meteorology and Water Management in Warsaw (IMWM).

In physiographic terms, Lublin is located in the northern part of the Lublin Upland. The city developed on the Bystrzyca River, along the lower sections of the catchment of its tributaries, namely the Krężniczanka, Czechówka, Czerniejówka, and Ciemięga Rivers. The Bystrzyca River catchment occupies 1,315.5 km^2. Agricultural land constitutes 39.5% (including arable land 33.3%) of the land use structure in the city (147.5 km^2). The forest and shrub cover amounts to 11.6%, developed and urbanised areas take up 43.4%, surface waters 2.7%, and areas of other land use 2.8%.

The total annual precipitation in Lublin is 560 mm. Outflow from the Bystrzyca River equals 125.7 mm, including 67.8 mm in the winter half-year, and 57.9 mm in the summer half-year (Michalczyk 2012). The river discharge regime is even, with a maximum in spring, and a minimum in late summer. Groundwater alimentation is dominant. The discharge rate in the urban section depends on the water supply from the upper parts of the catchment area. The Bystrzyca River in Lublin has a discharge of approximately 3.0 m^3 s^{-1}. The mean specific runoff in the upper part of the Bystrzyca River catchment slightly exceeds 4.0 dm^3 s^{-1} km^{-2}. In the lower part, it decreases to 3.5 dm^3 s^{-1} km^{-2}.

The documentation of the effect of the city's area on discharges into the Bystrzyca River and its tributaries involved the establishment of 9 automatic water gauge stations on rivers and in the vicinity of Lublin (Figure 1), as well as 2 stations recording water discharge in storm channels. The measurement network of the Department of Hydrology is composed of "Thalimedes" water gauges by OTTO Messtechnik, with a float sensor permitting continuous water level measurement. The readings of the gauges, supplemented with systematic monthly discharge measurements, permits the assessment of the volume and the dynamics of water discharge from the city's area, including the process of development of surface runoff, its volume and duration. The authors' own materials are supplemented by hydrological materials from IMWM, which were collected on the Bystrzyca River from two water gauges installed in Lublin and Sobianowice.

The water gauges recorded water discharge into the area within the city's boundaries and below the Zemborzycki Reservoir, as well as water stages and discharges in the centre and below the city (Figure 1). The specific urbanised (differential) catchment includes areas adjacent to the Bystrzyca River between water gauges in the dam (Zapora) and in Jakubowice (including the discharge of post-sewage waters from the sewage treatment plant), as well as the lower, strongly urbanised parts of the Czerniejówka (below Mętów) and Czechówka River catchments (below the Open Air Village Museum), with an area of 188.6 km^2. The precipitation volume calculation was based on data from IMWM and material from the Department of Meteorology and Climatology of MCSU.

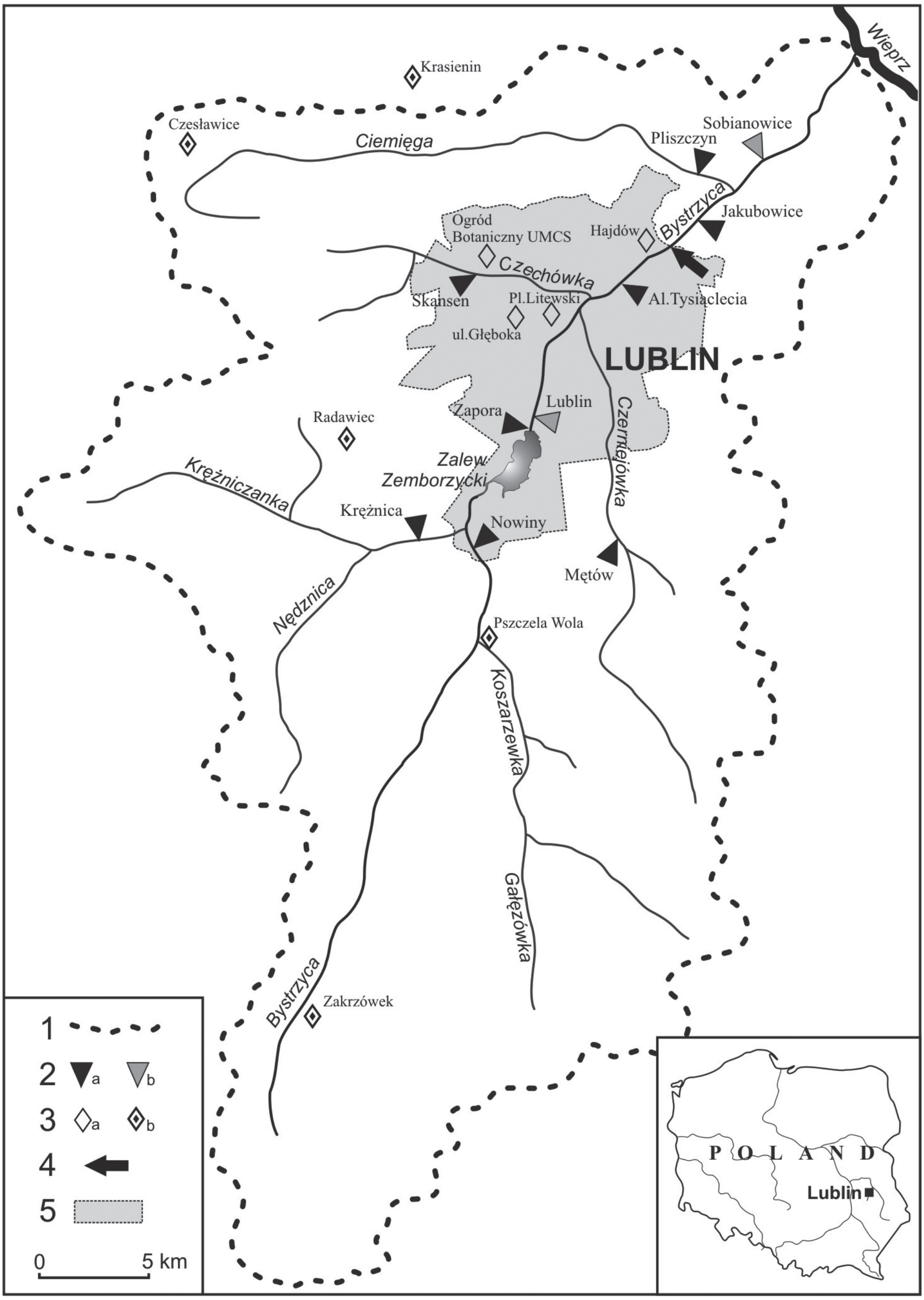

Figure 1 Distribution of measurement sites: 1 – watershed of the Bystrzyca River catchment, 2 – water gauge (a – MCSU, b – IMWM), 3 – precipitation station (a – MCSU, b – IMWM), 4 – discharge of post-sewage waters, 5 – area of Lublin. Source: own construction based on data from the Department of Hydrology.

The values of water discharge in the Bystrzyca River are considerably dependent on the exploitation of groundwater resources in Lublin, and the amount of post-sewage waters discharged from the Municipal Sewage Treatment Plant in Hajdów. This issue was investigated using detailed data from MWSC in Lublin. This permitted us to distinguish between the water intake and sewage disposal fluctuations typical of the Lublin agglomeration, i.e. so-called daily, weekly, annual, and holiday sociohydrological cycles. The groundwater table and range of the lowered water level were determined using materials from the Department of Hydrology and measurements systematically taken in MWSC.

OVERVIEW OF THE HYDROGEOLOGICAL CONDITIONS

The Bystrzyca River catchment, and particularly the city of Lublin, is an area distinguished by its high consumption of water resources. This is determined by a high level of groundwater intake for the purpose of meeting the city's municipal and industrial demands (355 thousand inhabitants). All the water intakes in the vicinity of Lublin almost exclusively use the groundwater resources circulating in the cracked Upper Cretaceous and Palaeocene rocks. Water intake in Lublin corresponds to more than 90% of the entire groundwater intake in the Bystrzyca River catchment.

The main groundwater reservoir which constitutes the catchment's water resources, is composed of carbonate Upper Cretaceous and Palaeocene rocks developed as gaizes, limestone, and marls. The carbonate rocks are covered with a thin layer of post-glacial sands or silt formations. The surface formations are distinguished by good water permeability, which is reflected in the low density of the river network. The groundwater collected in the Bystrzyca River catchment occurs in cracked Upper Cretaceous and Palaeocene rocks, and in sandy-gravel Quaternary formations. The groundwater usually constitutes one water reservoir, including the hydraulic connection between the Cretaceous, Tertiary, and Quaternary aquifers and multi-aquifer formations. In natural conditions, they are in balance with the drainage of surface waters. A single water table occupies a predominant part of the area. It is inclined towards the Bystrzyca River valley and its tributaries. In the river valleys, groundwater occurs just under the surface of the flood terraces, and in plateau areas, at a depth of 30-50 m. In natural conditions, the strong relationship of groundwater with surface waters is manifest in a high and even supply of groundwater to rivers. In the zones of influence of water intakes, in the areas of depression cones, this is manifest in the infiltration of surface waters.

WATER MANAGEMENT IN LUBLIN

Lublin is a city with long traditions (it obtained its city rights in the 14th century), including its water management. From the beginning of its existence as a settlement, and later as a city, it was strongly related to its water resources, and particularly those of the Bystrzyca, Czechówka, and Czerniejówka Rivers. The oldest traces of settlements are found in the forks of these rivers. In historical times, fluvial waters were used to propel milling equipment and sawmills.

The inhabitants were initially provided with surface waters, but the use of nearby springs soon followed. The first documents which mention water supply systems in Lublin come from as early as the 15th century. In the first half of the 15th century, a water supply system functioned in the city with a capacity of 4-5 $m^3 h^{-1}$. It supplied water through the Bystrzyca River valley from Wrotków (Bartoszewski et al. 2000). In the early 20th century, a modern water intake was established in the city centre, and another in 1929 in Wrotków. This initiated the exploitation of the modern-day supply system, using perfect quality groundwater resources. The intensification of economic activity led to systematic changes in water management in the urban area: marshy valley beds were meliorated, and the existing mill dams were eliminated. Rivers were regulated. Their course was subject to straightening and embankment. A fragment of the Czechówka River was covered. The main communication routes of the city were established in river valleys.

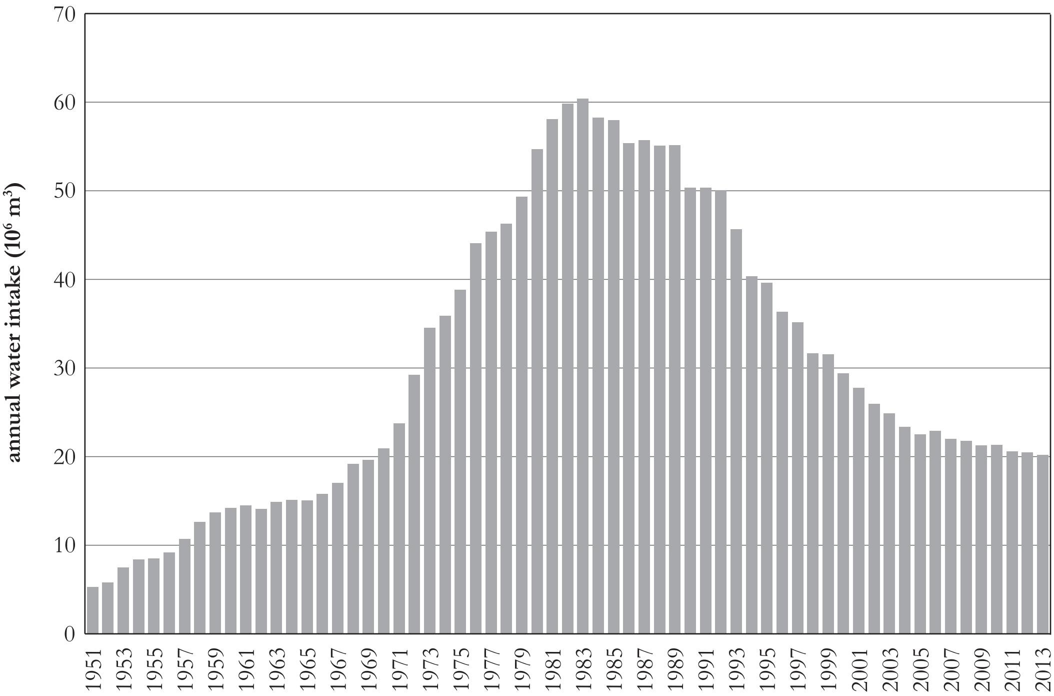

Figure 2 Annual water intake in Lublin in the years 1951-2013.
Source: own construction based on data from the MWSC in Lublin.

The current water demand of Lublin is met almost exclusively by supplying groundwater. The city includes large groundwater intakes concentrated in a relatively small area. The long-term concentrated exploitation of groundwater resulted in the development of a depression cone in Lublin, common for all of the intakes. Determination of the range and depth of the depression cone was based on the comparison of the current water table with that recorded in 1955, when the effect of the economy on the environment was relatively low.

The city's development caused an increase in the amount of water collected for economic and industrial purposes. The highest water consumption was recorded in 1983, when 60.4 million m^3 of water was used for the city's needs (Figure 2). The largest range of the depression cone, exceeding 200 km^2, and a local decrease in the water table exceeding 10 m, were determined in the early 1990s, when more than 50 million m^3 of water was used annually. In the following years, the depression cone was filled, and its range decreased (Michalczyk 1997). This was due to a somewhat increased precipitation, and considerably lower exploitation of groundwater resources. In the years 2004-2006, at an intake of approximately 23 million m^3 annually, the area of the depression cone was maintained at a level of approximately 120 km^2. In the years 2011-2013, with water levels at their highest in the previous five decades, the range of the lowered groundwater table amounted to 110 km^2. The extensive range of the depression cone is determined by the distribution of intakes in river valleys throughout the city. In 2013, in the zones of local watersheds, the water table was approximately the same as that from 1955. A more considerable lowering of the quasi-stable water level, while not exceeding 4 m, was only determined in the vicinity of some of the wells of the main water intakes of MWSC.

RIVER ALIMENTATION IN THE URBAN AREA

In the Bystrzyca River catchment above Lublin, groundwater remains in hydraulic drainage balance with surface waters. This results in a high contribution of water from underground resources in the outflow. In natural conditions, underground feeding constitutes 3/4 of the total outflow. In the area of the city, the discharge of rivers depends on water feeding from the upper parts of the catchment. In the conditions of the quasi-natural environment, the rivers carried low volumes of water: the Bystrzyca River 3.1 $m^3 s^{-1}$, the Czerniejówka River 0.7 $m^3 s^{-1}$, and the Czechówka River 0.2 $m^3 s^{-1}$ (Michalczyk et al. 1983). Below the city, the Bystrzyca River is continuously supplied with post-sewage waters with a volume of approximately 0.65 $m^3 s^{-1}$. These are groundwaters used for economic purposes, collected from drilled wells, and they considerably affect the volume of discharges in periods of low water levels.

A decrease in the groundwater table resulting from intensive exploitation of groundwater through drilled wells caused a change in the hydrodynamic balance between groundwater and surface waters in the area of Lublin. In periods of low groundwater levels, discharge in the rivers of Lublin along their urban sections usually decreases, particularly as a result of the infiltration of water from the river channels into the groundwater resources (Michalczyk 2012). The rivers transport water through the city, and the volume of water flowing along the urban section depends on the water feeding from the upper parts of the catchment. In the urban area, the rivers are continuously fed with post-sewage waters, and episodically with waters from surface runoff supplied by the network of rain channels. The area of Lublin includes 113 storm sewers; 44 of them supply water directly to the Bystrzyca River, 26 to the Czechówka River, and 43 to the Czerniejówka River. The catchments of the sewers occupy densely populated areas with a very high degree of surface non-permeability. They vary from several tens to several hundred hectares. The network collects precipitation and snowmelt waters from approximately 1/4 of the city's area. According to the data from MWSC, the total length of the storm sewers amounts to approximately 481 km, including the main channels with a length of 44.3 km. In periods of intensive precipitation or snowmelt, temporary discharges in the Bystrzyca River (Figure 3) increase several times, and the contribution of groundwater supply decreases to even less than 10%.

The discharge structure of the Bystrzyca River and its tributaries is dominated by groundwater feeding. The role of surface runoff increases in the urban area. Within the city, discharges expressed in relative measures decrease. This suggests a change in the conditions of the rivers' feeding. Only after the collection of post-sewage waters does the Bystrzyca River regain its "normal" water stages, related to the supply of waters collected through the system of drilled wells. According to the collected material, the rhythm of fluvial discharge in the agricultural areas was even, with slightly increased flows following higher precipitation. Intensive surface runoff developed in the urban area, causing a change in the discharge regime, particularly when high water levels reached 2 m. Moreover, the discharges of the lower Bystrzyca River below the supply of waters from the sewage treatment plant show a specific hourly variability, reflecting the rhythm of life of Lublin's inhabitants.

Changes in the discharge of the Bystrzyca River in Lublin are presented in Figure 3. The figure includes hourly discharges of the Bystrzyca River above (dam) and below Lublin (Jakubowice), as well as precipitation values in July 2011. The figure does not take into consideration discharges from the Czechówka and Czerniejówka Rivers. They have a minor effect on the resources of the Bystrzyca River. The discharges of the Bystrzyca River below the city were even, with a very slight response to precipitation water supply. An increased flow in the upper part of the catchment is reflected in the profile below Lublin, with no considerable increase in the runoff volume. The increased flow is accompanied by single short-term surface runoffs which result from the inflow of water from the storm sewers. Below the city (Jakubowice), high increases in discharge following precipitation are observed, as well as the hourly rhythm of discharge of post-sewage waters from the municipal sewage treatment plant.

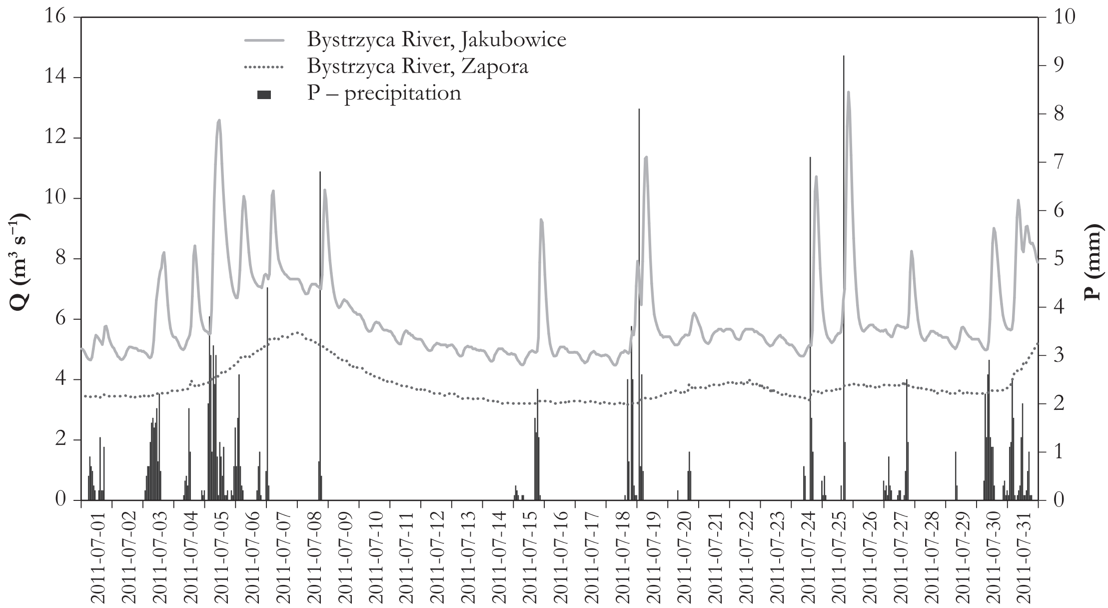

Figure 3 Hourly precipitation totals in Lublin and discharges of the Bystrzyca River below and above the city in July 2011. Source: own construction based on data from the Department of Hydrology, IMWM, and the Department of Meteorology and Climatology.

SURFACE RUNOFF – HIGH WATER LEVELS

The growing residential development in a considerable part of the city, the increasing number of industrial plants, roads, and railways, as well as paving squares and pavements causes a decrease in groundwater retention. The limited possibility of water infiltration in the conditions of varied land relief favours the development of surface runoff. Direct measurements suggest that in periods with no precipitation, the rivers along the urban section are not supplied with water. During precipitation, a quite rapid increase in water levels in the rivers is recorded.

During precipitation, surface runoff develops quite rapidly on paved active surfaces. Rain water from urbanised areas is directed to storm drains. It causes a relatively fast increase in the discharge of the rivers. Observations suggest that intensive precipitation of several millimetres causes a high increase in water levels and fluvial discharges below the city (Figure 3).

A similar situation concerning water runoff from the agricultural and urban catchment is also recorded in the winter season. Runoff from the urban catchment appears considerably earlier. This also results from the application of chemical agents on roads. Such runoff usually causes high water level flows with the volume depending on the precipitation and temperature conditions, as well as ground freezing. It should be emphasised that, based on daily discharges recorded as morning readings of water levels, it is difficult to determine the volume of water runoff from an urban area. Such calculations are only possible in the case of automatic water gauges recording changes in water levels at one-minute intervals.

In urbanised areas, in the conditions of a dense stormwater network, the time of outflow concentration was reduced. This results in the discharge of vast amounts of water from urban catchments through collector channels into rivers. The runoff volume and intensity depends on the type and rate of precipitation. Figure 4 presents 10-minute

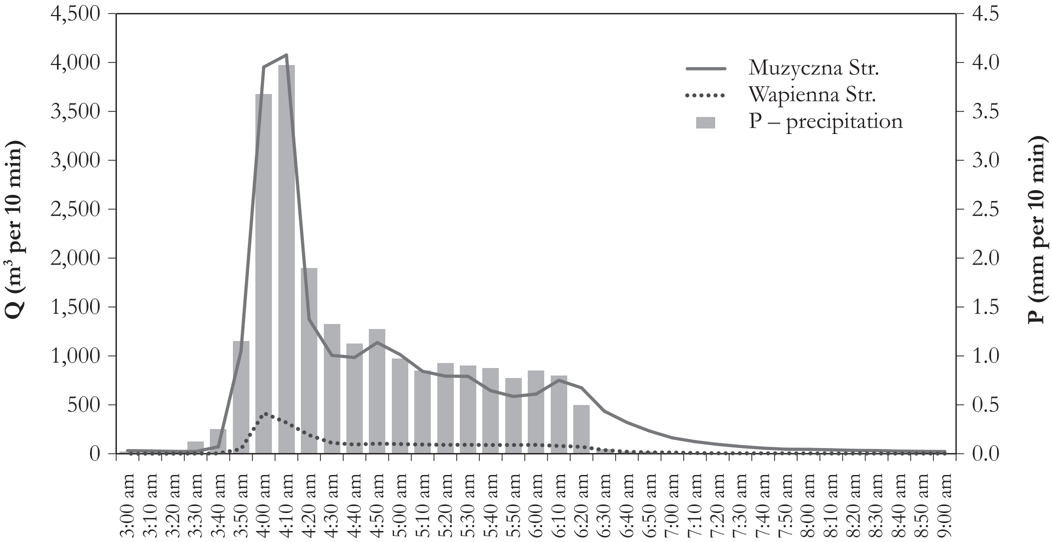

Figure 4 Ten-minute precipitation totals and outflows from two catchments of storm sewers: Muzyczna and Wapienna Streets in Lublin. Source: own construction based on data from the Department of Hydrology, IMWM, and the Department of Meteorology and Climatology.

precipitation totals and water discharge values from two storm sewers with different areas, namely 50.4 and 343.6 ha. These exist in the western part of the city, in an area with a loess relief. The larger catchment includes an extensive and urbanised dry valley, while the smaller one is from the watershed zone and the adjacent symmetrical lowering. Storm sewers respond to precipitation very rapidly, and the volume of water inflow depends on the precipitation intensity. Initial retention is relatively low. Therefore, surface runoff is quickly activated. Its effects are most evident in the Bystrzyca River below the city (Figure 3). After precipitation, water outflow is maintained for 2-4 more hours. This is also determined by the extent of the stormwater network (Figure 4).

The high correlation between precipitation and outflow permits the calculation of the volume of water runoff which depends on precipitation (Michalczyk 2012). Using coefficients of the runoff from various surfaces, the contribution of particular areas of the city in the development of runoff and the volume of water outflow from the urbanised area of Lublin can be balanced.

OUTFLOW RHYTHM

The variability of fluvial discharge in the lower section of the rivers is determined by the effect of the city, irrespective of the occurrence of precipitation and snowmelt. Part of the water continuously flows from the municipal sewage treatment plant, collecting the used municipal and industrial waters. The functioning of the plant in Hajdów involves equal amounts of sewage inflow from the city and outflowing post-sewage waters. Otherwise, the plant would be flooded at the moment of inflow of higher amounts of municipal waters.

Sewage is drained through a separate and mixed sewage system. Household sewage is transported through collector channels to the sewage treatment plant in Hajdów. Precipitation waters running off the urban area are directed to storm channels, and eventually to rivers. Observations of the amount of sewage inflowing to Hajdów during precipitation showed that precipitation waters inflow together with sewage. This results from leaks in the stormwater and sanitary installations, and the lack of stormwater systems in certain districts of the city.

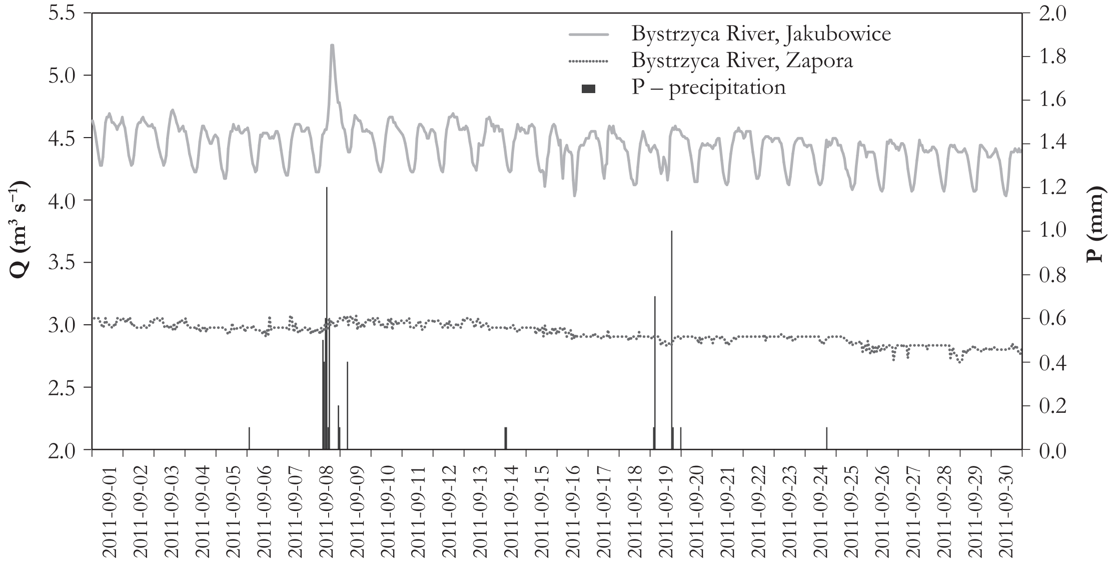

Figure 5 Hourly precipitation totals in Lublin, and discharge values in the Bystrzyca River above and below the city in September 2011. Source: own construction based on data from the Department of Hydrology, IMWM, and the Department of Meteorology and Climatology.

The water levels and discharges in the lower Bystrzyca River below the supply of waters from the sewage treatment plant show a specific variability which reflects the rhythm of life of the inhabitants of Lublin. The rhythm, which indicates the economic activity of the city, is called the sociohydrological cycle. It results from the uneven consumption of water by users, and the resulting disposal of sewage. The activity of water consumption and sewage disposal changes in seasonal and in hourly rhythms. The daily sociohydrological rhythm is the most characteristic (Sposób 2007, 2012). It has two maximums and one minimum. It is observed on almost all days of the year, except for days with precipitation and holidays, which are distinguished by a changed rhythm. Irrespective of the volume of inflowing sewage, the daily rhythm of changes is retained. The weekly sociohydrological cycle can be particularly observed on certain days of the week: on Saturdays, when high amounts of sewage inflowing to Hajdów are recorded, and on Sundays, with low water intake volumes and low sewage outflows. The annual rhythm corresponds to changes in the number of inhabitants in Lublin, and, as shown before, the specificity of the mixed sewage system. In this cycle, summer months and holidays are clearly distinguished by lower inflows of sewage, particularly due to a lower number of inhabitants using water. Holiday seasons are very interesting in this context, including Christmas, Easter, Corpus Christi, and so-called “long weekends”. On days which precede holidays, sewage inflows are very frequently high until late night hours. On the following days, their values are among the lowest in the year. From the monthly perspective, the lowest inflows of post-sewage waters were recorded in July and August, although with a somewhat shifted hourly rhythm. This is due to the holiday season and the absence of students. The highest water inflow was recorded in October.

The supply of post-sewage waters to the Bystrzyca River affects its natural discharge regime. Increased volumes of sewage are accompanied by an increase in discharges in the Bystrzyca River. The distribution of hourly discharges in the river has a daily rhythm, which is repeated almost every day (Figure 5, 6). The lowest discharges are recorded around noon, usually with a minimum at 12:00. From 14:00,

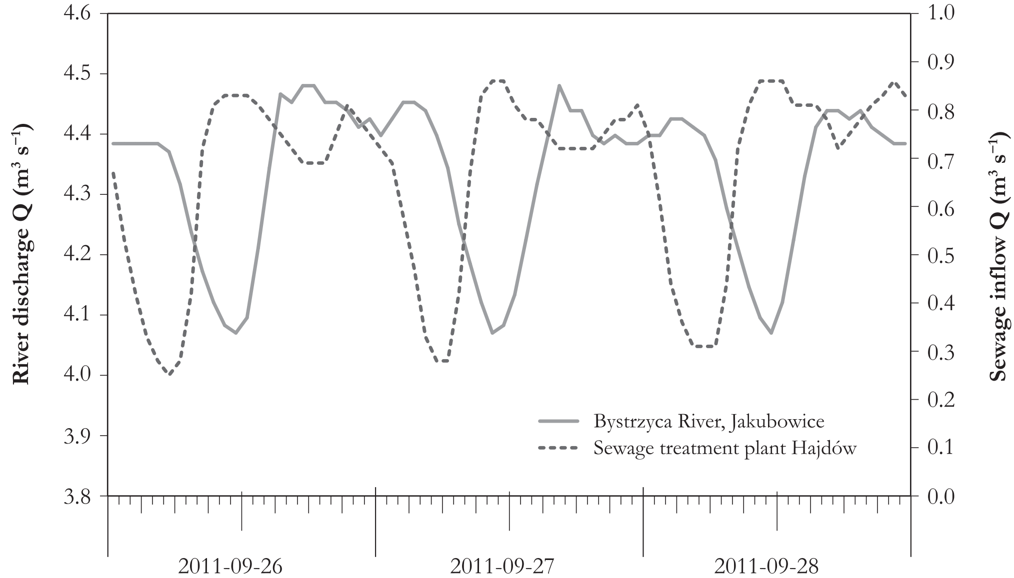

Figure 6 Hourly sewage inflows to the sewage treatment plant in Hajdów, and discharges in the Bystrzyca River on 26-28 September 2011. Source: own construction based on data from the Department of Hydrology, IMWM, and the Department of Meteorology and Climatology.

the discharges increase and reach the highest values around 21:00-22:00. The highest discharge is frequently recorded at night (around midnight) or early in the morning (2:00-3:00 am). The highest hourly discharges in a day can also typically last for many hours. The usual rhythm of discharges in the Bystrzyca River is typical of periods with no precipitation or surface runoff (e.g. during snowmelt). The daily rhythm of the functions of Lublin's inhabitants and the functions of the wastewater treatment plant determine the discharges of the Bystrzyca River.

A comparison of graphs which describe the hourly discharges in the Bystrzyca River and the hourly values of sewage inflow to the sewage treatment plant shows an evident shift in extreme values. It is the time needed for the movement of larger or smaller volumes of post-sewage waters from the sewage discharge site in Hajdów to the water gauge profile in Jakubowice.

In natural conditions, hourly discharge fluctuations in the Bystrzyca River are not considerable (Figure 3). Substantial changes in discharges occur during rapid flood flows in profiles located in urbanised areas. In urbanised catchments, under conditions of a dense stormwater network, the time of concentration of outflow is reduced. This results in the discharge of high volumes of water from the urban catchments through collector channels into the rivers. The time of water inflow is short, slightly longer than the duration of precipitation.

The rhythm of sewage inflow to Hajdów reflects the city's economic activity. Hourly discharge values in the Bystrzyca River in Jakubowice permitted the determination of the effect of the post sewage water supply on the discharge into the Bystrzyca River. The calculations were performed according to programmes which eliminated disturbances in the natural rhythm caused by the inflow of precipitation or snowmelt waters.

Discharge fluctuations in the Bystrzyca River caused by the inflow of post-sewage waters differ in volume and time of inflow on particular days

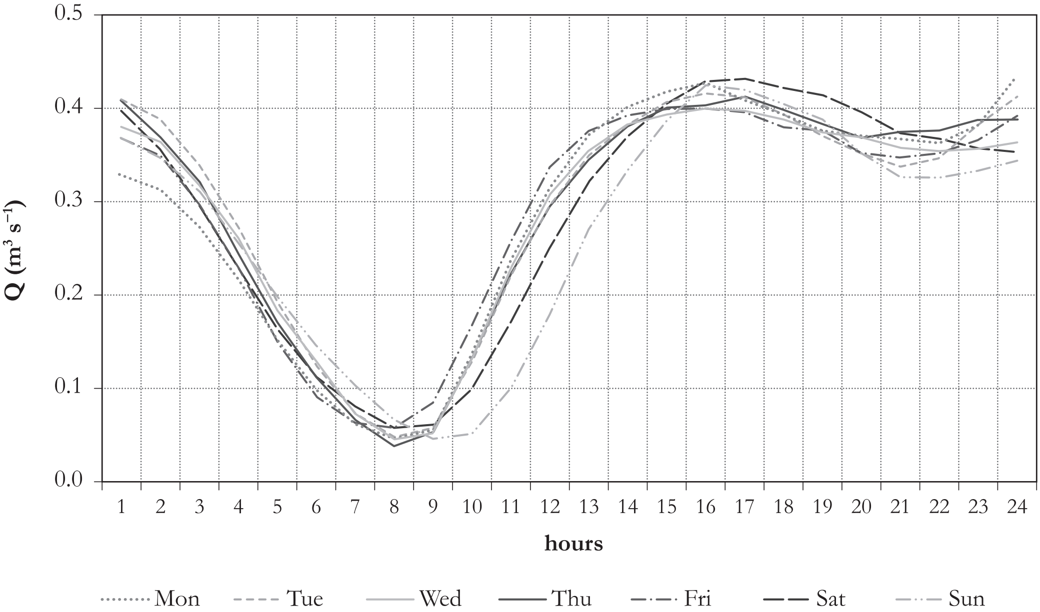

Figure 7 Variation in mean hourly discharge values in Jakubowice on particular days of the week in 2011.
Source: own construction based on data from the Department of Hydrology.

of the week (Figure 7). It is not the entire volume of post-sewage waters, but only their variable part. If a mean of 0.684 $m^3 s^{-1}$ of such waters was discharged during 2011, their volume during a day usually varied from 0.4 to 0.8 $m^3 s^{-1}$. This change, which was a result of the rhythm of post-sewage water supply, was recorded in water gauge profiles below Lublin. The highest water consumption was recorded on Saturdays. On Sundays, water intake occurred slightly later than on the remaining days (Figure 7).

The contribution of post-sewage waters or sewage in fluvial discharges is important for the biological life of the river receives them. In the case of the Bystrzyca River, it particularly depends on the discharges into the river itself. The contribution of post-sewage waters to the mean discharges in the Bystrzyca River amounts to approximately 20% (Michalczyk et al. 1983). In the case of the lowest discharges, it reaches 38% (in the years 1991-1995) or even 40% (Michalczyk ed. 1997; Sposób 2007), which is of considerable importance for the river's ecosystem.

CONCLUSIONS

The development of Lublin depends on good management of the water resources of the Bystrzyca River catchment. The city's demand for water is met almost exclusively by the groundwater resources retained in Upper Cretaceous marls and gaizes. They are high quality waters with physical and chemical properties developed during the long filtration process in the rock environment. Water intakes are concentrated in a relatively small area. This results in the development of a depression cone in Lublin, common for all of the intakes. Its size depends on atmospheric alimentation and the volume of water collected for municipal and economic purposes. The high atmospheric supply recorded over the last fifteen years, as well as a decreased exploitation of groundwater, led to the reduction of the area of the depression cone from 200 km^2 in 1992 to 110 km^2 in recent years.

River valleys and channels in Lublin are distinguished by good hydraulic contact between groundwater and surface waters. In natural conditions, in conditions of drainage balance, a high and even supply of groundwater to river channels is recorded. At a high level of exploitation of groundwater, fluvial waters feed the bedrock, particularly in periods of low water levels. The structure of outflow from the Bystrzyca River and its tributaries was dominated by the underground supply, and the role of surface runoff increased in the urbanised area. Within the city, discharges expressed in relative measures decreased. This suggests a change in the conditions of the rivers' alimentation. It was only after receiving post-sewage waters that the Bystrzyca River regained its "normal" water stages. This was related to the supply to the rivers of water collected through the system of drilled wells.

Water levels and discharges in the lower Bystrzyca River below the point of supply of waters from the sewage treatment plant show specific variability, reflecting the rhythm of life of Lublin's inhabitants. The activity of water consumption and waste disposal changes in a seasonal and an hourly rhythm. The daily sociohydrological cycle is the most typical, with two maximums and one minimum.

In urbanised areas, under the conditions of a dense stormwater network, the time of outflow concentration was reduced. This results in the supply of high volumes of water from the urban catchments through collector channels into rivers, which causes rapid water level increases below the city. As a consequence of building development, the infiltration of water to the groundwater resources decreases, and the surface runoff which determines the rapid development of high water levels below the urbanised areas increases. The industrialisation and urbanisation of urban areas is increasingly manifest in the effect of anthropogenic factors on the conditions of the occurrence, outflow, and quality of water.

References

Akan, A. O., Houghtalen, R. J. 2003: *Urban Hydrology, Hydraulics, and Stormwater Quality: Engineering Applications and Computer Modelling*. John Wiley and Sons, Inc., 392 pp.

Bartoszewski, S., Michalczyk, Z., Piszcz, J. 2000: Hydrological consequences of the water management in the Lublin area. *Acta Universitatis Palackianae Olomucensis, Fac. Res. Nat. Geographica* 36, 19–25.

Cheng, S., Wang, R. 2002: An Approach for Evaluating the Hydrological Effects of Urbanization and its Application. *Hydrological Processes* 16, 1403–1418.

Cuo, L., Lettenmaier, D. P., Mattheussen, B. V., Storck, P., Wiley, M. 2008: Hydrologic prediction for urban watershed with the Distributed Hyrology-Soil-Vegetation Model. *Hydrological Processes* 22, 4205–4213.

Deletic, A. 1998: The first flush load of urban surface runoff. *Water Resources* 32 (8), 2462–2470.

Dobija, A. 1975: Wpływ urbanizacji na stosunki wodne. *Czasopismo Geograficzne* 46 (1), 73–78.

Hollis, G. E. 2010: The effect of urbanization on floods of different recurrence interval. *Water Resources Research* 11, 431–435.

Huong, H. T. L., Pathirana, A. 2013: Urbanization and climate change impacts on the future urban flooding in Can Tho city, Vietnam. *Hydrology and Earth System Sciences* 17, 379–394.

McPherson, M. B. ed. 1974: *Hydrological effects of urbanization* (Studies and reports in hydrology, No 18). UNESCO, Paris, 280 pp.

McPherson, M. B. ed. 1977: *Research on urban hydrology, Volume 1* (Technical paper in hydrology, No 15). UNESCO, Paris, 185 pp.

Michalczyk, Z. ed. 1997: *Strategia wykorzystania i ochrony wód w dorzeczu Bystrzycy*. Wyd. UMCS, Lublin, 192 pp.

Michalczyk, Z. ed. 2012: *Ocena warunków występowania wody i tworzenia się spływu powierzchniowego w Lublinie*. Wyd. UMCS, Lublin, 268 pp.

Michalczyk, Z., Łoś, M., Sawicka-Ner, Z. 1983: Zasięg oddziaływania ujęć wód podziemnych miasta Lublina. *IG, Prace Hydrogeologiczne – seria specjalna* 16, 1–83.

Russo, B., Gómez, M., Martínez, P., Sánchez, H. 2005: Methodology to study the surface runoff in urban streets and design of drainage inlets systems. Application in a real case study. *10th International Conference on Urban Drainage, Copenhagen, Denmark, 21-26 August 2005*. (http://www.flumen.upc.edu/admin/files/72.pdf)

Sposób, J. 2007: Cykle socjohydrologiczne aglomeracji lubelskiej i ich oddziaływanie na przepływy Bystrzycy. In **Michalczyk, Z. ed.** *Obieg wody w środowisku naturalnym i przekształconym*. Wyd. UMCS, Lublin, 487–494.

Sposób, J. 2012: Analiza dynamiki dopływu ścieków do oczyszczalni w Hajdowie. In **Michalczyk, Z. ed.** *Ocena warunków występowania wody i tworzenia się spływu powierzchniowego w Lublinie*. Wyd. UMCS, Lublin, 196–211.

Résumé

Hydrologické konsekvence urbanizace: případová studie Lublin (Polsko)

Příspěvek prezentuje hydrologické důsledky změn vodních poměrů v oblasti polského města Lublin, a to především v kontextu změn zásob podzemních vod a jejich dopadu na vodnost řek, dynamiky povrchového odtoku a jeho dopadu na výši průtoku řek a také vlivu vodního hospodářství na režim průtoku řeky Bystrzyce.

Naplnění cílů příspěvku bylo dosaženo jednak na základě hydrologických, hydrochemických a hydrogeologických měření a pozorování uskutečněných pracovníky Oddělení hydrologie Univerzity Marie Curie-Skłodowské v Lublinu a taktéž bylo využito dat Institutu meteorologie a vodního hospodářství ve Varšavě týkajících se obecního vodovodu a kanalizace města Lublin.

Z fyzickogeografického hlediska se Lublin nachází v severní části Lublinské vrchoviny. Město původně situované na řece Bystrzyci se postupně rozšířilo i do dolních částí povodí jejích přítoků (Krężnica, Czechówka, Czerniejówka a Ciemięga).

Povodí řeky Bystrzyce zaujímá plochu 1 315,5 km^2. Rozloha města samotného činí 147,5 km^2, přičemž podíl jednotlivých ploch funkčního využití na rozloze města je následující: zastavěné plochy 43,4 %, zemědělské plochy 39,5 %, lesní plochy 11,6 %, vodní plochy 2,7 % a ostatní plochy 2,8 %.

Systémy zásobování obyvatelstva i průmyslu města Lublin vodou se postupně mění. V současné době je poptávka města po vodě saturována téměř výhradně podzemními zdroji, které jsou vázány na slíny a horniny svrchní křídy. V případě těchto podzemních zdrojů se jedná o vodu vysoké jakosti, jejíž fyzikální a chemické charakteristiky se formují dlouhodobým procesem filtrace v horninovém prostředí. Čerpání podzemní vody se koncentruje na území relativně malé rozlohy, což má za následek utváření depresního kužele v oblasti města Lublin. Jeho velikost je závislá na atmosférických srážkách a množství vody využívané pro komunální a ekonomické potřeby. Vyšší atmosférické srážky zaznamenané v posledních patnácti letech v kombinaci se snížením využívání podzemních vod vedly ke zmenšení rozsahu kužele z 200 km^2 v roce 1992 na 110 km^2 v současnosti.

Údolí i koryta výše zmíněných řek vykazují dobré hydraulické kontakty mezi povrchovými a podpovrchovými vodami. V přirozených podmínkách rovnoměrného odvodňování je registrováno velké a pravidelné zásobení koryt řek podpovrchovými vodami. Nicméně při vysoké exploataci podpovrchových vod dochází k tomu, že voda řek zásobuje reservoár podpovrchových vod, zvlášť v období nízkých stavů. Ve struktuře odtoku řeky Bystrzyce a jejich přítoků dominuje podpovrchové zásobování, role povrchového odtoku narůstala v urbanizovaných oblastech. V prostoru města se průtok vyjádřený relativními mírami snížil, což poukazuje na změny podmínek zásobení řek. Pouze po přijetí odpadních vod získala řeka Bystrzyca zpět „normální“ vodnatost. Skutečnost má souvislost se zásobením řek vodou zachycenou pomocí systému vrtaných studní.

Stav vody a průtok dolní Bystrzyce, resp. části Bystrzyce nacházející se pod čistírnou odpadních vod, vykazují specifickou variabilitu odrážející životní

rytmus obyvatel města Lublin. Míra spotřeby vody i vypouštění odpadních vod se mění v denním i sezónním rytmu, přičemž nejcharakterističtější je denní socio-hydrologický cyklus se dvěma maximy a jedním minimem.

V urbanizovaných oblastech s hustou kanalizační sítí byla doba koncentrace odtoku snižována. To má za následek zásobení řek velkým objemem vody z městské části povodí, což způsobuje rapidní nárůst hladiny vody pod městem. V důsledku rozvoje výstavby dochází k poklesu infiltrace zásob podpovrchových vod vodami povrchovými a naopak k nárůstu povrchového odtoku, který determinuje rychlý vývoj vysokých vodních stavů pod urbanizovanými územími. Industrializace a urbanizace městských oblastí se čím dál tím více projevují v obecném působení antropogenních faktorů ovlivňujících výskyt, odtok a kvalitu vody.

Article received May 17, 2014
Accepted for publication June 22, 2014

Please cite this article as
Michalczyk, Z., Chmiel, S., Głowacki, S., Sposób, J. 2014: The hydrological consequences of urbanisation: Lublin case study (SE Poland). *Acta Universitatis Palackianae Olomucensis, Facultas Rerum Naturalium, Geographica* 45 (1), 23–36.

Article available on-line at
http://geography.upol.cz/geographica-45-1b